African Rainfall as a Precursor of Hurricane-Related Destruction on the U.S. East Coast

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Abstract

This paper describes a predictive relationship between West African rainfall and U.S. hurricane-spawned destruction, which is based on information for the 42-yr period 1949–90. It is shown that above-average rainfall during the previous year along the Gulf of Guinea, in combination with above-average rainfall in the western Sahel during June and July, is linked to hurricane-spawned destruction along the U.S. East Coast occurring after 1 August, which is 10–20 times greater than in years when pre-1 August precipitation for these West African regions is below average. Similar hurricane-spawned damage along the U.S. Gulf Coast shows only a negligible relationship with African rainfall. Hurricane-caused deaths for both U.S. coastal regions also show a similar association with West African rainfall.

1. Introduction

The incidence of intense Atlantic hurricanes exhibits very large variations on both interseasonal and interdecadal time frames. Table 1 lists six measures of Atlantic seasonal tropical storm and hurricane variability extracted from data for the last 42 years (Jarvinen et al. 1984; Neumann et al. 1987). No single measure of tropical cyclone activity seems to adequately define the diverse combination of factors that occur during each hurricane season. For example, as shown in Fig. 1, intense hurricane activity was significantly greater during the 1950s and 1960s, in comparison with the 1970s and 1980s (except for 1988 and 1989). However, little or no decadal-scale trend was observed in the frequency of named storms in this time period (see also Gray 1990; Landsea 1991; Landsea and Gray 1992).

Because the incidence of tropical storms and weaker hurricanes has not varied much in recent decades, the public has been largely unaware of the extent of the decrease in the less-frequent intense hurricanes and of the resulting reductions in U.S. coastal hurricane-related destruction that has occurred since 1970. These large multidecadal variations become clearly evident only when analyzed in terms of the seasonal totals of Saffir–Simpson (see Simpson 1974; Saffir 1977) category 3–5 (see Table 2) hurricanes. Differences are most evident in the frequency of intense landfalling hurricanes along the U.S. East Coast, including peninsular Florida, but not for landfalling intense hurricanes along the Gulf Coast.

Year-to-year variations in Atlantic hurricane activity are well related to seasonal variations of 1) the El Niño; 2) the quasi-biennial oscillation of equatorial 30-mb and 50-mb stratospheric winds; 3) Caribbean Basin-Gulf of Mexico sea level pressure anomaly; 4) lower-latitude Caribbean basin 200-mb zonal wind anomaly; and 5) the new and very important parameter of West African rainfall (Gray 1984a,b, 1990; Landsea 1991). The association with variations of West African rainfall is of particular interest in relation to seasonal and decadal variations of hurricane-spawned destruction in the United States and in the Caribbean basin (Landsea 1991; Gray and Landsea 1991). This paper discusses a surprisingly strong predictive relationship between West African rainfall occurring prior to 1 August and subsequent hurricane-spawned destruction along the East Coast occurring after 1 August (nearly all U.S. hurricane-spawned destruction occurs after 1 August).

2. Hurricane statistics and measures of hurricane intensity

We have recently completed a study of the damage due to U.S.-landfalling hurricanes, wherein damage estimates were stratified by Saffir–Simpson hurricane-intensity category. Table 2 lists a summary of various Saffir–Simpson storm characteristics, including typical central pressure, maximum sustained wind, and storm-surge height, plus observed and assumed coastal destruction values that are associated with each of the five intensity categories. As noted by Sheets (1990), there has been a growing acceptance of the Saffir–Simpson scale as the best overall measure of hurricane intensity. Hurricane destruction potential goes up rapidly as the Saffir–Simpson scale

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Table 1. Summary of Atlantic tropical cyclone statistics and West African rainfall data for 1949–90. The numbered columns show yearly incidence of 1) named storms, 2) named storm days, 3) hurricanes, 4) hurricane days, 5) category 3–5 hurricanes, 6) category 3–5 hurricane days, 7) precipitation anomaly expressed as standardized deviations for the early season (prior to 1 August) rainfall, and 8) as in column 7 but for June through September western Sahel rainfall.

	NS	**NSD**	**H**	**HD**	**IH**	**IHD**	**ES**	**J–S**
Year	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1949	13	62	7	22	3	5.25	−0.16	−0.10
1950	13	98	11	60	8	18.75	0.57	1.49
1951	10	58	8	36	5	8.25	−0.31	0.32
1952	7	40	6	23	3	6.75	0.62	1.00
1953	14	64	6	18	4	6.75	0.73	0.55
1954	11	44	8	32	2	9.50	0.39	0.77
1955	12	82	9	47	6	17.25	1.20	1.46
1956	8	30	4	13	2	2.75	0.16	0.40
1957	8	38	3	21	2	6.50	−0.02	0.52
1958	10	56	7	30	5	9.50	0.55	1.28
1959	11	41	7	22	2	4.25	−0.45	0.06
1960	7	30	4	18	2	11.00	0.55	0.51
1961	11	71	8	48	7	24.50	0.94	0.77
1962	5	22	3	11	1	0.50	−0.31	0.19
1963	9	52	7	37	2	7.00	0.21	−0.09
1964	12	71	6	43	6	14.75	1.00	0.88
1965	6	40	4	27	1	7.50	−0.28	0.54
1966	11	62	7	42	3	8.75	−0.37	0.07
1967	8	58	6	36	1	5.75	0.24	0.75
1968	7	26	4	10	0	0.00	−0.36	−0.75
1969	17	84	12	40	5	6.75	0.78	0.55
1970	10	24	5	7	2	1.00	−0.30	−0.45
1971	13	63	6	29	1	1.00	−0.30	−0.30
1972	4	21	3	6	0	0.00	−0.64	−1.16
1973	7	33	4	10	1	0.25	−0.61	−0.80
1974	7	32	4	14	2	4.25	−0.16	−0.23
1975	8	43	6	20	3	2.25	0.42	0.34
1976	8	45	6	26	2	1.00	−0.48	−0.56
1977	6	14	5	7	1	1.00	−0.72	−0.91
1978	11	40	5	14	2	3.50	−0.04	−0.18
1979	8	44	5	22	2	5.75	0.06	−0.54
1980	11	60	9	38	2	7.25	−0.46	−0.68
1981	11	61	7	22	3	3.75	0.06	−0.34
1982	5	16	2	6	1	1.25	−0.54	−0.88
1983	4	14	3	4	1	0.25	−0.72	−1.31
1984	12	51	5	18	1	0.75	−0.72	−1.16
1985	11	51	7	21	3	4.00	−0.18	−0.50
1986	6	23	4	10	0	0.00	−0.56	−0.37
1987	7	37	3	5	1	0.50	−0.50	−0.76
1988	12	47	5	24	3	8.00	0.29	0.18
1989	11	66	7	32	2	10.75	0.71	0.58
1990	14	68	8	27	1	1.00	−0.31	−0.95
Means	9.9	47.0	5.9	23.8	2.5	5.7		
St. dev.	2.9	20.0	2.2	13.3	1.8	5.5		

increases from its lowest (category 1) to its highest (category 5) value.

The next-to-last column on the right of Table 2 shows the median of normalized (to 1990) U.S. hurricane-spawned destruction by each of the five Saffir–Simpson classes of landfalling hurricanes. These destruction estimates were derived from an empirical analysis of normalized hurricane-destruction data for the 42-yr period between 1949 and 1990. Coastal-damage amounts were obtained from the annual seasonal-hurricane summaries published in the *Monthly Weather Review* for 1949–90. Damage was normalized to 1990 equivalent dollars by accounting for inflation of construction costs and coastal population increases (Landsea 1992). A storm-by-storm breakdown of damage was made by normalizing the long-term damage values to 1990 dollars using the monthly U.S. Department of Commerce Implicit Price Deflator for Construction (U.S. Department of Commerce 1991) to account for inflation. A second factor for normalization of damage to 1990 dollars is to account for the large increases in population along the U.S. coastal zones. Sheets (1990) noted a 60% rise in the number of Atlantic coastal inhabitants, a 250% increase in coastal Texas, and an enormous 400% increase in coastal Florida between 1950 and 1985. Obviously, adjusting for only inflation severely underestimates the potential for damage today where populations have increased substantially.

This paper thus utilizes both the Implicit Price Deflator for Construction as well as population changes for specific locations. Hurricane King, which struck Miami in 1950 and caused $28 million in damage, provides a good example of the normalization procedure. Since 1950, construction costs have increased by 470% (a factor of 5.70) and the population along coastal southeast Florida has increased by 500% (a factor of 6.00). This combined factor of 34.2 normalizes the damage to $957 million in 1990 dollars.

We find that destruction by landfalling hurricanes of intensity category 4 or 5 is typically 100 to 300 times greater than the destruction caused by category 1 hurricanes and about 10 to 30 times greater than that due to landfalling category 2 hurricanes. Thus, we estimate incremental values of U.S. hurricane destruction by Saffir–Simpson category to be related approximately to the scale shown in the right-hand column of Table 2.

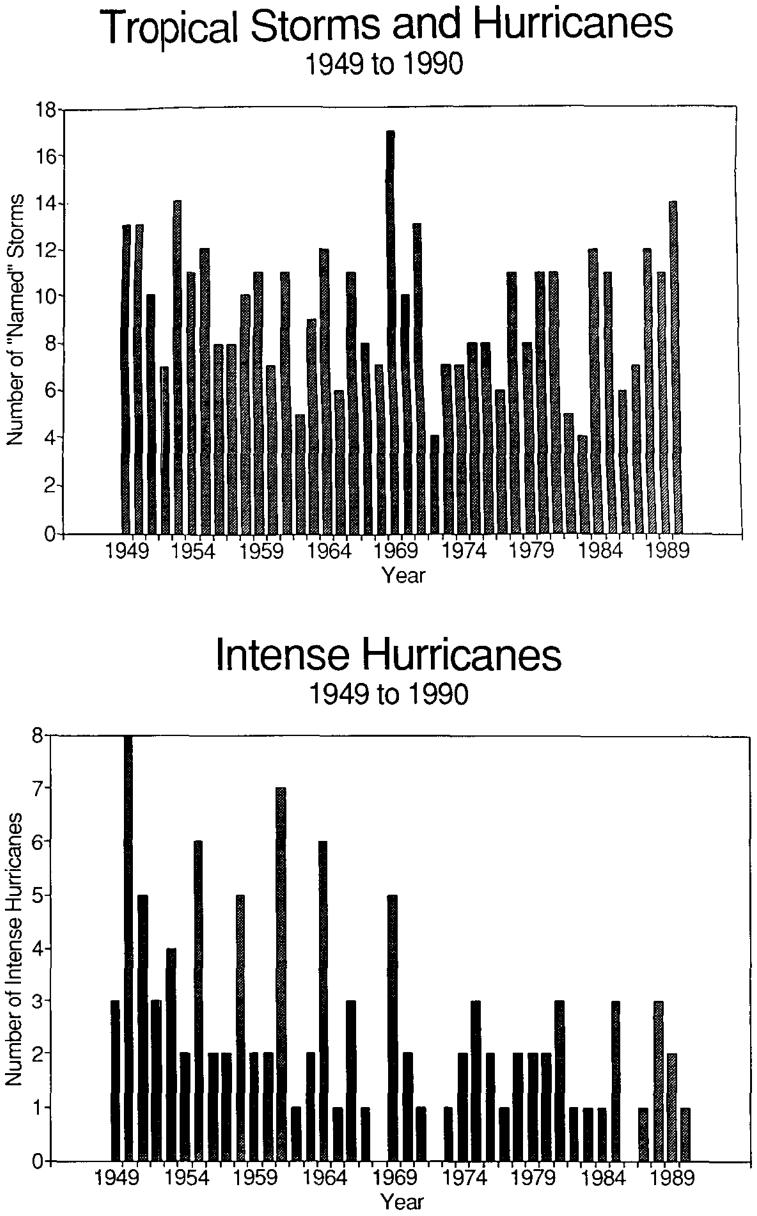

Fig. 1. Annual incidence of named storms (tropical storms and hurricanes) versus intense-hurricane days between 1949 and 1990.

The contrast between the vast damage by category 4 Hurricane Hugo in 1989 ($7.247 billion in 1990 dollars) versus the minimal damage effects due to 1989 category 1 hurricanes Chantal ($103 million) and Jerry ($75 million) illustrates these differences quite well. The exponential rise in hurricane-destruction potential indicated in Table 2 accommodates our observation that that the wind and storm-surge destruction by hurricanes is more closely associated with the third or fourth power of maximum wind speeds than with linear variations of the maximum wind speed. Of course, any storm can vary significantly from this standard, wherein destruction by individual cyclones of a specific category may greatly differ due to variations in the character of coastal terrain or building density along the coastline over which each hurricane comes ashore.

TABLE 2: Wind speed, surge, and estimated relative destruction criteria for the five categories of the Saffir–Simpson scale.

Saffir–Simpson	Range of central pressure (mb)	Maximum sustained wind speed (m s^{-1})	Storm surge (m)	Typical destructive potential	Median normalized U.S. destruction in $ millions	Assumed relative U.S. destruction
1	≥980	33–42	1.0–1.7	minimal	24	1
2	965–979	43–49	1.8–2.6	moderate	218	10
3	945–964	50–58	2.7–3.8	extensive	1108	50
4	920—944	59–69	3.9–5.6	extreme	2274	100
5	<920	>69	>5.6	catastrophic	5933	250

The increased destruction by intense hurricanes is primarily a result of wind and storm-surge damage and, to a lesser extent, rainfall-spawned flood damage. Hurricane flood damage does not necessarily increase with Saffir–Simpson category, rainfall-induced flood damage from tropical storms and hurricanes being largely a function of the speed at which tropical cyclones traverse an area, the large-scale structure of the storm, and local terrain characteristics. Some of the largest tropical cyclone-induced flood damage in the United States has come from lesser-intensity tropical storms and category 1 hurricanes [e.g., Tropical Storm Allison in 1989 ($510 million), category 1 Hurricane Agnes in 1972 ($5.928 billion), and category 1 Hurricane Diane in 1955 ($6.741 billion)].

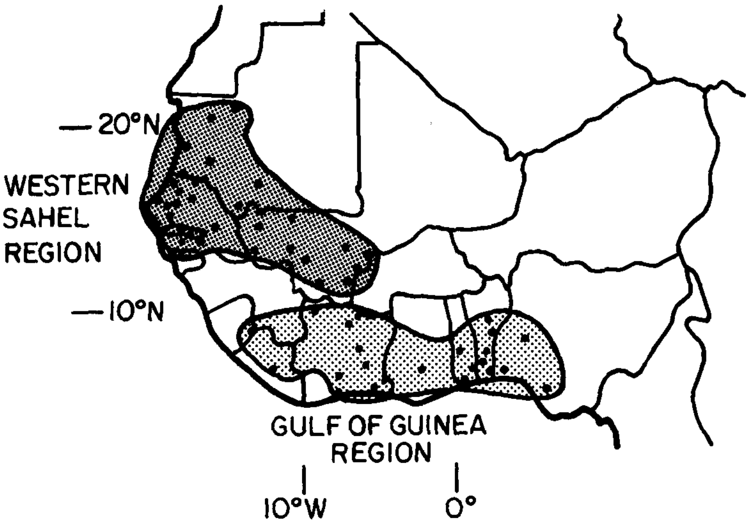

FIG. 2. Locations of 38 rainfall stations that make up the western Sahel precipitation index, as well as the 24 Gulf of Guinea precipitation stations. August-to-November rainfall within the Gulf of Guinea region shows a predictive signal for western Sahel rainfall and hurricane activity during the following season. June–July rainfall in the western Sahel region provides a strong predictive signal for the following August-through-October hurricane activity (see Landsea 1991).

3. Interannual predictability of hurricanes from African rainfall

a. *Incidence of U.S.-landfalling intense hurricanes and West African rainfall*

We have recently observed that intense (category 3–5) Atlantic hurricane activity is greatly enhanced when the western Sahel region of West Africa (Fig. 2) has above-average precipitation. Similarly, intense-hurricane activity is much suppressed when concurrent precipitation in this region is below average (Gray 1990). Recent analyses by Landsea and Gray (1992) show very high correlations between year-to-year variations of intense hurricane days between 1949 and 1990 and year-to-year variations of western Sahel rainfall. Additional analyses (Landsea 1991) show that West African rainfall data can also be used in a predictive sense to forecast variations in intense hurricane activity and U.S. hurricane-spawned destruction in subsequent seasons. We find that the rainfall that fell in the Gulf of Guinea region (Fig. 2) between August and November of the previous year, in combination with the June–July precipitation for the current year in the western Sahel region (collectively known as the "early season combination rainfall index"), is typically a very good predictor of intense hurricane activity during the forthcoming August–October period. Figure 3 shows values for this combination rainfall index wherein rainfall during August through November of the previous year in the Gulf of Guinea region is weighted 0.3 June–July western Sahel precipitation weighted 0.7. The values in Fig. 3 are expressed in terms of a standardized deviation (a "Z-score"). These combined rainfall anomaly index values, which are available by 1 August each year, are compared with the seasonal incidence of category 3–5 hurricane days in Table 1. Approximately 60% of the subsequent seasonal variance (linear correlation of 0.78) of intense hurricane days is explained (i.e., forecast) by the combined rainfall index.

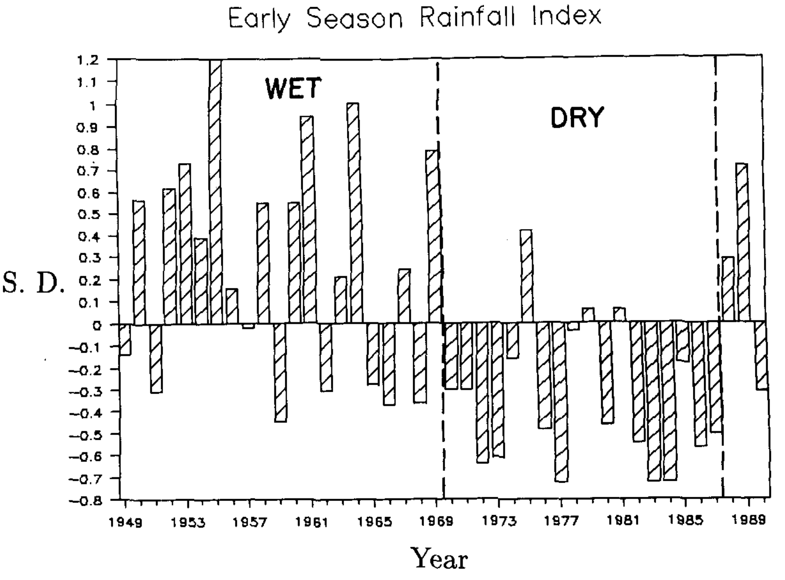

Fig. 3. Bar graph of the early-season rainfall-anomaly index, which includes the previous year August–November rainfall from the Gulf of Guinea (weighted 0.30) and June–July western Sahel rainfall (weighted 0.70). Rainfall is expressed as standardized deviations from the 42-yr average (from Landsea 1991).

It is curious that African rainfall prior to the first of August is so highly correlated with subsequent seasonal values of intense-hurricane activity. Gulf of Guinea rainfall during the prior fall season is likely related to the strength of the West African monsoon in the following year through positive feedbacks of evapotranspiration and soil moisture. Conversely, as the monsoon develops in June and July, western Sahel rainfall is a good indication of how far north and how strong the West African monsoon trough establishes itself. The usefulness of the first two months of the Sahel rainy season (June and July) for forecasting the remainder of the rainy season was first indicated by Bunting et al. (1975) when the Sahel drought was becoming a persistent feature in the mid-1970s.

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Table 3 further demonstrates the strong association between early season West African rainfall and intense-hurricane activity. Note that the number of named storms (i.e., tropical storms and minor hurricanes) remains little changed between wet and dry years. However, more than ten times as many intense-hurricane days occurred in association with the ten wettest as compared to the ten driest early-season rainfall values during this 42-yr period. Figure 4 shows the differences in intense-hurricane tracks when data are stratified according to decreasing amounts of early-season rainfall during the corresponding preseason periods. Observe that the average annual incidence of intense-hurricane days in each 7-yr group is progressively lower, with seasonal mean values of 12.8, 9.2, 4.9, 3.9, 3.2, and 0.5 days, respectively. In view of this association, early seasonal African rainfall (i.e., prior to 1 August) should be closely monitored, as it is a very good indicator (hence, forecast) of the amount of intense-hurricane activity likely to follow after 1 August. This is especially useful in that, historically, over 98% of all intense-hurricane activity occurs during the August through November period (Fig. 5), allowing a true "forecast" to be made by 1 August from African rainfall information.

b. West African rainfall and hurricane destruction within two U.S. coastal areas

To normalize hurricane destruction in terms of 1990 dollars, we have utilized factors to accommodate both inflation and increased coastal property development. During the 42-yr period of 1949-90 there has been a total of approximately $76.7 billion (in equivalent 1990

TABLE 3. Comparison of the early-season (i.e., prior to 1 August) West African rainfall index for the ten driest and ten wettest seasons during 1949–1990 versus the number of tropical storms (weaker than hurricane force), minor (category 1 or 2) hurricanes, intense (category 3–5) hurricanes, and intense-hurricane days. Early season rainfall includes Gulf of Guinea rainfall for August through November during the previous year (weighted 0.3) and current year June–July western Sahel region rainfall (weighted 0.7).

Ten driest years

Ranking of dry year	**Standardized deviation of rainfall**	**Tropical storms only**	**Minor hurricanes (Cat. 1–2)**	**Intense hurricanes (Cat. 3–5)**	**Intense-hurricane days**
1984 *(extremely dry)*	−0.72	7	4	1	0.75
1983	−0.72	1	2	1	0.25
1977	−0.72	1	4	1	1.00
1972	−0.64	1	3	0	0.00
1973	−0.61	3	3	1	0.25
1986	−0.56	2	4	0	0.00
1982	−0.54	3	1	1	1.25
1987	−0.50	4	2	1	0.50
1976	−0.48	2	4	2	1.00
1980 *(moderately dry)*	−0.46	2	7	2	7.25
Mean	−0.64	2.6	3.4	1.0	1.23

Ten wettest years

Ranking of wet year	**Standardized deviation of rainfall**	**Tropical storms only**	**Minor hurricanes (Cat. 1–2)**	**Intense hurricanes (Cat. 3–5)**	**Intense-hurricane days**
1955 *(extremely wet)*	1.20	3	3	6	17.25
1964	1.00	6	0	6	14.75
1961	0.94	3	1	7	24.50
1969	0.78	5	7	5	6.75
1953	0.73	8	2	4	6.75
1989	0.71	4	5	2	10.75
1952	0.62	1	3	3	6.75
1950	0.57	2	3	8	18.75
1958	0.55	3	2	5	9.50
1960 *(moderately wet)*	0.55	3	2	2	11.00
Mean	0.76	3.8	2.8	4.8	12.72
Ratio wet/dry		1.5/1	0.8/1	4.8/1	10.3/1

dollars) of U.S. hurricane- and tropical storm-spawned destruction. Of this value, approximately 10% was caused by a total of 61 landfalling tropical storms, 19% by the 40 landfalling category 1 and 2 hurricanes, 44% by 19 landfalling category 3 hurricanes, and 27% by a total of only 6 landfalling category 4 and 5 hurricanes.

The eastern U.S. coastline can be approximately separated into two regions that experience differing landfalling hurricane responses to pre-1 August West African rainfall: the East Coast (including the Florida peninsula) and the Gulf Coast (including the Florida panhandle). The two regions are depicted in Fig. 6.

Table 4 lists the percentage of 1949–90 hurricane destruction in the East Coast and Gulf Coast areas that occurred during each of six 7-yr groupings shown previously in Fig. 4. Note in Table 4 that the Gulf Coast has experienced a different distribution of hurricane damage in relation to West African rainfall than has the East Coast. Damage along the East Coast is increased dramatically in the two wettest 7-yr groupings in comparison to the other four drier groupings. The

Gulf Coast damage amounts show little sensitivity to West African rainfall.

A comparative listing of West African early season rainfall prior to 1 August, ranked from highest to lowest yearly amounts, is shown in Table 5; 1955 was the wettest and 1984 the driest. Included in this rainfall-ranked data are hurricane destruction values for each year in millions of 1990 dollars. Note that although the mean damage values for each region are similar, hurricane destruction on the Gulf Coast is not well associated with West African rainfall prior to 1 August, whereas East Coast damage is.

Most of those years with large amounts of hurricane-spawned destruction on the East Coast were also years when early season West African rainfall was above normal. Conversely, below-average early-season rainfall years were typically associated with very little East Coast and Florida peninsula hurricane-spawned destruction. There have been, of course, some heavy early-season West African rainfall years wherein no hurricane-spawned destruction occurred. These exceptions are reasonable, given that hurricane formation and track statistics for individual seasons are highly variable. Landfall on the East Coast during individual years is also dependent upon factors other than early-season West African rainfall, and hence, an association in individual seasons cannot be expected. However, when averaged over several years, very clear signals emerge. For example, total normalized hurricane destruction on the East Coast during the ten years with the greatest early-season rainfall during 1949–1990 was $23.70 billion; this

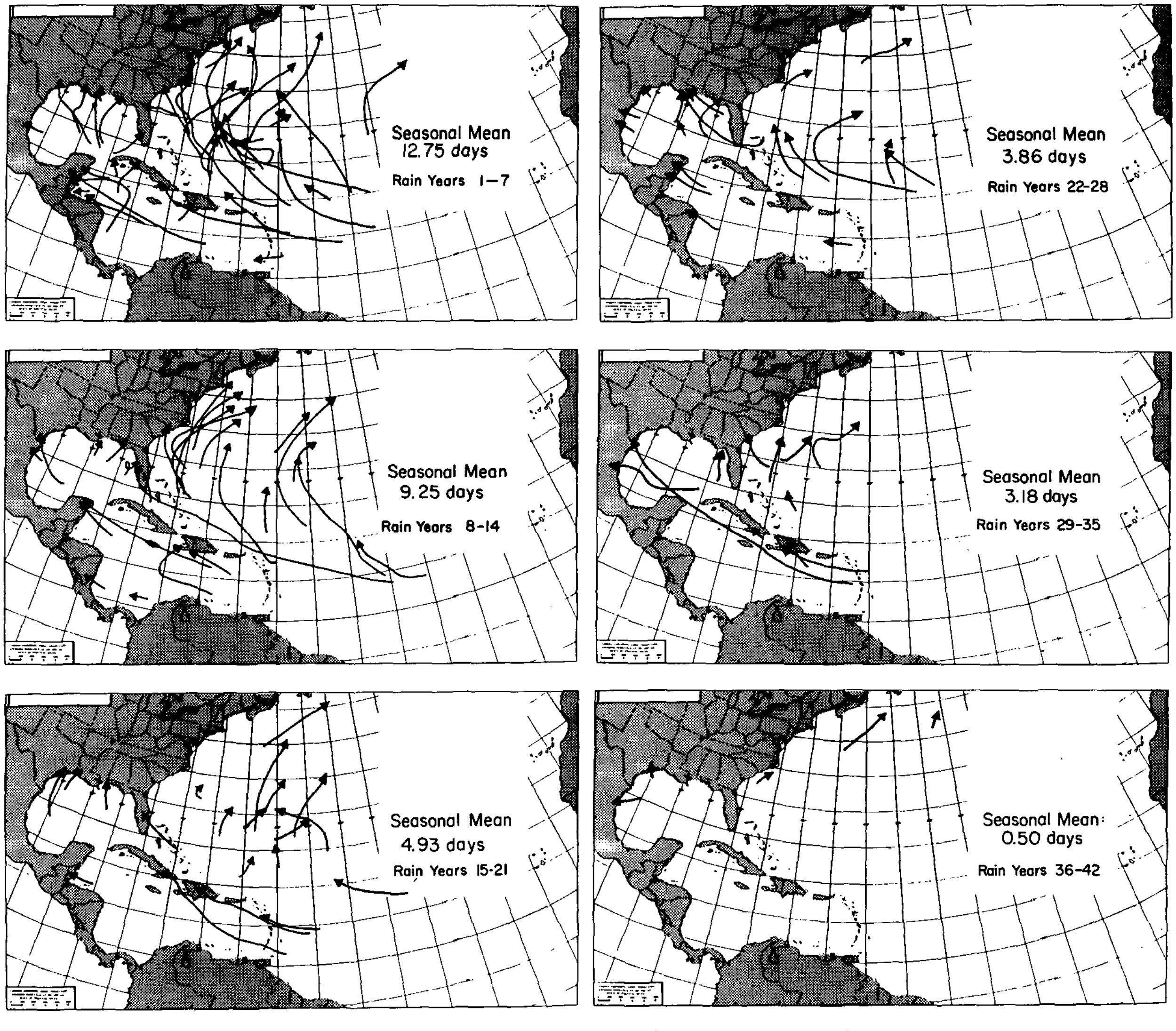

FIG. 4. Comparison of intense (category 3–5) hurricane tracks stratified into six groups of seven years each based upon the early season (prior to 1 August) rainfall amounts. The top left panel includes the seven wettest individual years, and the bottom right panel is a composite of the seven driest years. (The years included in each group are listed in Table 5.)

TABLE 4. Comparison of normalized (1990) average U.S. hurricane-destruction values for the same West African early season rainfall stratification as in Fig. 5. Column 2 shows the mean West African rainfall anomaly for each 7-yr period, expressed as standardized deviations.

Ranking of rainfall (7-yr increment)	**Mean rainfall anomaly (s.d.)**	**Intense hurricane day**	**U.S. East Coast percent of total damage**	**U.S. Gulf Coast percent of total damage**
1–7 *(wettest)*	+.85	12.5	55	27
8–14	+.43	9.25	29	8
15–21	+.04	4.93	8	17
22–28	−.26	3.86	7	38
29–35	−.42	3.18	1	2
36–42 *(driest)*	−.64	0.50	0	8
Total			**100%**	**100%**

versus $0.30 billion for the ten driest early-season years. This difference amounts to a ratio of 79 to 1. By contrast, differences in Gulf Coast destruction during the ten wettest versus the ten driest years in West Africa are little more than two to one. Therefore, it is during the very wet early seasons in West Africa that East Coast destruction goes up so dramatically. It is remarkable that the probability of East Coast and Florida hurricane destruction should go up so dramatically during those years of high West African rainfall prior to 1 August. If hurricane destruction information were analyzed for the Caribbean region, we are confident that similar wet-versus-dry hurricane destruction would also be found. We are working to understand why West African rainfall anomalies greater than 0.4 standardized deviations above normal are associated with greatly increased amounts of intense-hurricane activity and potential U.S. coastal hurricane destruction over those seasons when West African rainfall is normal or below normal.

The comparatively poor association between West African rainfall and hurricane destruction along the U.S. Gulf Coast and Florida panhandle region is shown in Table 5; large amounts of hurricane destruction can occur along the Gulf Coast during very dry West African conditions. Notably, Hurricane Alicia (1983) caused 1990 normalized hurricane destruction of $2.71 billion in the Galveston–Houston region during what was the driest early-season western Sahel rainy season of the last 42 years. Intense-hurricane activity along the Gulf Coast typically occurs earlier in the season than along the East Coast (see Landsea 1992). For example, 7 of 13 (i.e., 54%) landfalling Gulf Coast category 3–5 hurricanes between 1949 and 1990 made landfall before 21 August, while only 1 of 12 (8%) East Coast intense hurricanes made landfall by this date. Whereas category 4 Hurricane Audrey (1957) made landfall on the Gulf Coast on 27 June, the earliest East Coast–Florida intense hurricane to make landfall (between 1949 and 1990) was Connie on 12 August 1955. Conversely, during the same period, only two intense hurricanes (15% of the total) made landfall along the Gulf Coast after 12

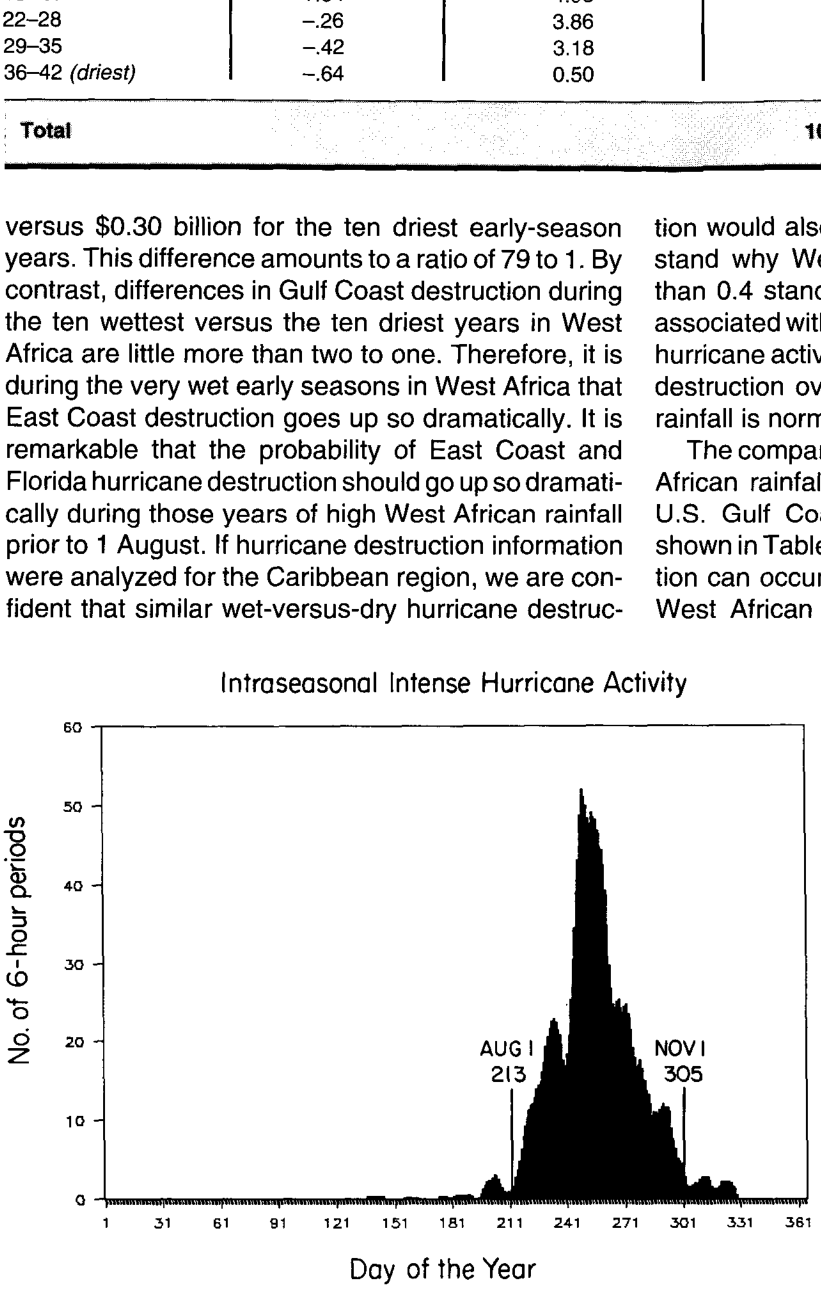

FIG. 5. Plot of Julian day versus intense-hurricane activity (nine-day running mean) using data for 1886 through 1989. Note that nearly all intense-hurricane activity occurs between 1 August and 1 November.

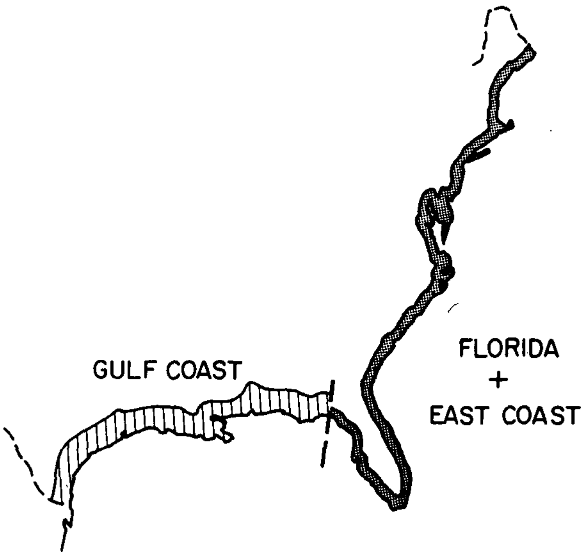

FIG. 6. Illustration of the two basic U.S. coastal regions that are observed to have different hurricane destruction responses to varying amounts of seasonal West African precipitation. The approximate separation point is the Apalachee Bay at Florida (from Landsea et al. 1992).

September, while six (50%) made landfall after this date along the East Coast.

We may generalize that intense hurricanes that make landfall along the Gulf Coast can form in climatological environments notably different from those of hurricanes that make landfall along the East Coast. In particular, hurricane activity affecting the Gulf Coast is much less related to West African rainfall than is hurricane activity along the East Coast. Illustrative examples include intense Gulf hurricanes Audrey (1957) and Alicia (1983), which did not develop from African waves, as do nearly all East Coast intense landfalling hurricanes. Typically, intense hurricanes landfalling in the Gulf are highly dependent upon meteorological conditions in the western Caribbean basin and Gulf of Mexico, which are much farther downwind from West Africa and hence are less responsive to circulation characteristics associated with African rainfall. Therefore, circulation features in the western Caribbean and Gulf of Mexico tend to be primarily responsible for the intensification of powerful and destructive hurricanes making landfall along the Gulf coastline, while African rainfall is much less of a contributing feature.

c. Incidence of U.S. vicinity intense hurricanes and West African rainfall

As landfalling U.S. hurricanes occur at a rate of about two in three years, it is difficult to obtain a large case sample of wet-versus-dry landfalling frequencies. Due to the long-running Sahel drought, this is particularly true for landfalling intense hurricanes in recent years. For example, there have been only three category 3–5 hurricanes landfalling along the East Coast and Florida peninsula in the last 30 years.

One can obtain a larger and more reliable statistical sample of the association of early-season West African precipitation with potential U.S.-influencing hurricanes by determining the number of hurricanes and the number of intense hurricanes that track to within 300-500 km of the vicinity of the U.S. coastline. If West African rainfall conditions can in this way be shown to be related to a large modulation of all hurricane activity in the vicinity of the U.S. coastline, then one might be able to demonstrate the modulating influence of early-season West African rainfall on hurricane activity. Over a long period, the number of landfall hurricanes should be a smaller fraction of the number of vicinity hurricanes.

For the purpose of this test, Fig. 7 shows the areas taken to be in the vicinity of the Gulf Coast, the Florida peninsula coastline, and the East Coast (EC). Table 6 shows the number of intense hurricanes and the number of hurricanes of all intensity classes passing within the vicinity of these three locations along the U.S. coastline during the ten wettest versus the ten driest years of 1949–1990. The probability (or P value) that these frequency differences might be by chance

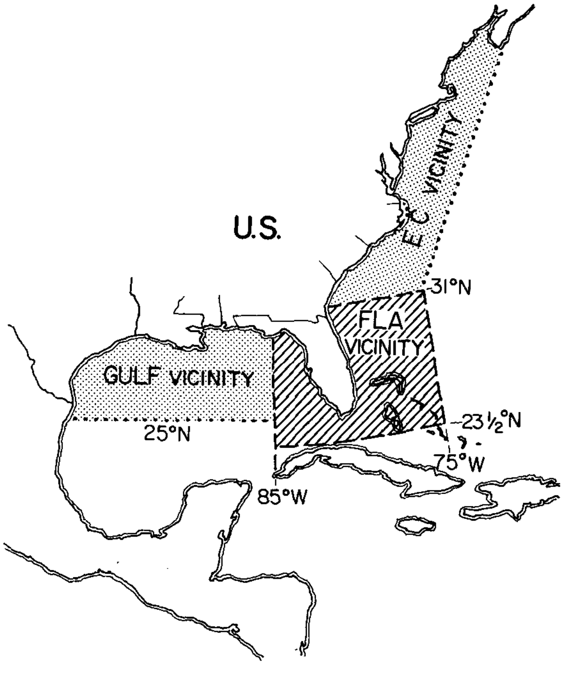

FIG. 7. Portrayal of the U.S. coastal areas designated as in the vicinity of the Gulf Coast, vicinity of the Florida peninsula, and the vicinity of the East Coast (EC).

TABLE 5. Ordered ranking of 42 yr of early-season (prior to 1 August) precipitation and concurrent yearly East Coast and Gulf Coast hurricane destruction in millions of 1990 normalized dollars. Year 1 has the highest rainfall, year 42 the lowest.

Year	East Coast damage	Gulf Coast damage	Year	East Coast damage	Gulf Coast damage
1. 1955	7825	0	22. 1974	0	380
2. 1964	3617	687	23. 1985	1075	3863
3. 1961	0	2396	24. 1965	1389	6719
4. 1969	0	5933	25. 1970	0	1894
5. 1953	9	4	26. 1971	45	202
6. 1989	7247	178	27. 1951	0	0
7. 1952	28	0	28. 1990	0	0
8. 1950	1033	0	29. 1962	0	0
9. 1958	0	0	30. 1968	50	0
10. 1960	3939	8	31. 1966	46	94
11. 1975	0	1352	32. 1959	104	68
12. 1954	5133	0	33. 1980	0	472
13. 1988	0	56	34. 1976	209	0
14. 1967	0	1137	35. 1987	1	0
15. 1963	0	109	36. 1982	0	0
16. 1956	0	228	37. 1986	1	2
17. 1979	651	3854	38. 1973	0	0
18. 1981	0	0	39. 1972	0	171
19. 1957	0	1354	40. 1977	0	20
20. 1978	0	0	41. 1983	0	2713
21. 1949	1888	119	42. 1984	89	0
			Mean	**817.8**	**809.8**

is also given. Each P value is obtained under the null hypothesis that a hurricane (or an intense hurricane) could occur with equal chance during either the wettest or the driest periods. Consequently, each two-sided P value is the sum of individual probabilities of the binomial distribution (characterized by P = 0.5, *n* being the sum of the two observed frequencies), which are as small or smaller than the individual probability associated with the observed pair of frequencies. P values are also given for the combined Florida peninsula and East Coast vicinities and for the combined U.S. coastline. Note the much greater frequency of intense hurricanes and all hurricanes in the vicinity of the combined Florida peninsula and the East Coast in the ten wettest years in comparison to the ten driest years. Nineteen intense hurricanes were observed within the vicinity of the Florida peninsula and the East Coast during the wettest period, but only three during the driest period. The probability (or P value) that these differences would occur by chance is 0.66 x 10^{-4}. For all hurricanes, the wet-versus-dry period for combined Florida peninsula and East Coast vicinities was 36 to 9, giving a probability by chance of 0.86 x 10^{-3}. However, no such strong wet-versus-dry modulation is observed in the vicinity of the Gulf Coast.

There can be little doubt that the rainfall within the western Sahel and the Gulf of Guinea region before 1 August is strongly associated with the amount of hurricane activity occurring within the vicinity of the Florida peninsula and the East Coast. But hurricane activity in the vicinity of the Gulf Coast is not much affected. If hurricane activity is shown to increase in the vicinity of the East Coast, then U.S. landfalling hurricane activity should also be altered by a comparable ratio.

4. U.S. hurricane deaths versus West African rainfall

If the incidence of U.S. landfalling intense hurricanes is well related to early-season West African rainfall, then a similar relationship should occur for U.S. deaths from these hurricanes. As shown in Table 7, this appears to be true. The annual number of U.S.-related hurricane deaths for the ten wettest early-seasonal rainfall years is much greater, particularly along the East Coast including the Florida peninsula—on average, nearly 60 times as many hurricane-related deaths occurring during the ten wettest seasons. Although these differences are striking, they are not strictly representative. Most of the wet periods occurred during the 1950s and 1960s when U.S. hurricane warning systems and civilian-defense procedures were not as well developed as in more recent years, although coastal population density was much lower in the earlier period. In general, it appears that a sizable modulation of U.S. hurricane-caused deaths may be linked to variations in West African rainfall.

5. Outlook for the 1990s and early 21st century

Although the western Sahel has experienced extremely dry conditions since 1970, this drought should not be expected to continue indefinitely. Long-running multidecadal Sahel droughts in the past have always been eventually replaced by rainy periods. It is likely that we will see a return to a period of normal or above-normal western Sahel rainfall conditions within the next decade. When and if this happens, we will almost certainly see a return to more frequent intense hurricanes along the East Coast and the Caribbean basin regions, which experienced a much greater amount of intense-hurricane activity during the last West African wet period of the 1950s and 1960s. It is unlikely that the next two decades will have as few intense hurricanes as have occurred during the last two decades.

It is unlikely that the next two decades will have as few intense hurricanes as have occurred during the last two decades.

The greatly increased population and property values along the U.S. Atlantic coastline and within the Caribbean basin since the late 1960s dictate that the return of the greater incidence of intense hurricanes will be accompanied by significantly greater coastal property damage (and likely more hurricane deaths). It is appropriate that the residents of the Atlantic coastal areas be aware of the prospects for a long-term increase in the incidence of potentially dangerous hurricanes during the coming decades. Note what happened in the Atlantic basin in 1988 and 1989 when the western Sahel experienced a temporary abatement in its drought conditions. No less than five category 4 and 5 hurricanes occurred in those two years, including the infamous hurricanes Gilbert and Hugo.

6. Summary

Given the close spatial proximity of West Africa to the tropical Atlantic, and the fact that the majority of Atlantic hurricanes are spawned by West African easterly waves, it is not surprising that variable aspects of African summer-monsoon rainfall and Atlantic intense-hurricane activity might be related. But what is new and surprising is the fact that they are so well related and that there is a multimonth time lag from rainfall to hurricane activity. This lag allows for multimonth predictability of hurricane activity just from a measurement of the rainfall alone. Figure 8 shows an idealized illustration of this relationship. As the majority of hurricane-related damage is due to the comparatively infrequent but very powerful storms, it becomes important that we carefully examine and fully appreciate both the annual and interdecadal variations of the occurrence of intense hurricanes. We believe that the strong precursor signals in seasonal rainfall prior to 1 August each year are a consequence of the strength and latitude of the West African monsoon trough as it becomes established in June and

TABLE 6. Comparison of the frequency of intense-hurricane and all hurricane tracks in the vicinity of various U.S. coastal locations (Fig. 7) during the ten wettest versus the ten driest early-season (prior to 1 August) West African rainfall years between 1949 and 1990 and the probability (or P value) of no wet-versus-dry relationship.

	Vicinity of Gulf Coast	**Vicinity of Florida Peninsula**	**Vicinity of East Coast**	**Vicinity of FL peninsula plus EC**	**Vicinity of whole U.S. coastline**
		No. of intense-hurricane tracks			
Ten wettest years	5	11	8	19	24
Ten driest years	3	2	1	3	6
P value of no difference	0.6291	0.0043	0.0106	0.66×10^{-4}	0.18×10^{-3}
		No. of all hurricane tracks			
Ten wettest years	10	18	18	36	46
Ten driest years	7	4	5	9	16
P value of no difference	0.7270	0.0225	0.0391	0.86×10^{-3}	0.0014

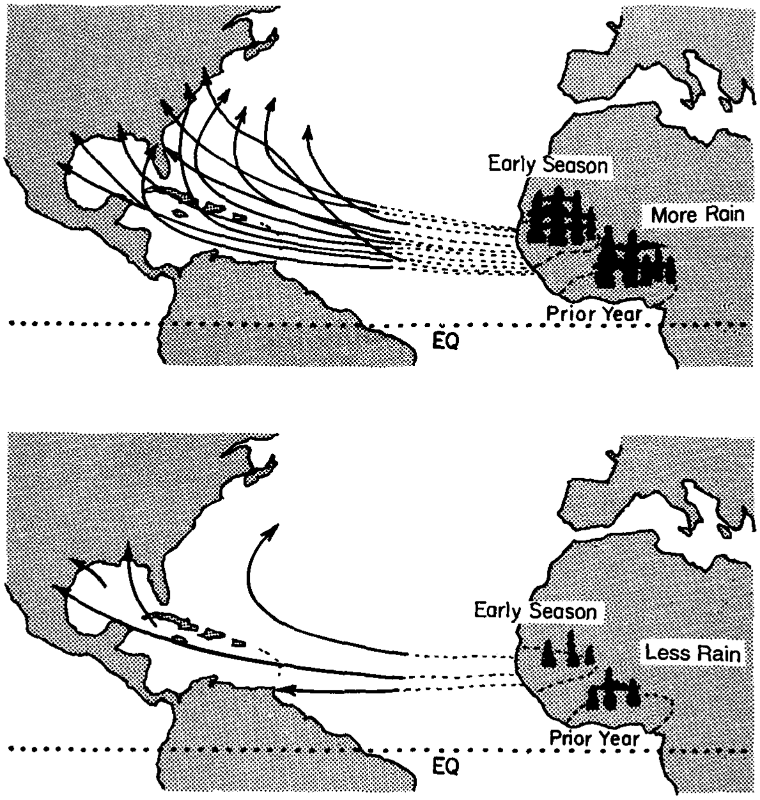

FIG. 8. Idealized rendering of the difference in composite intense-hurricane storm tracks during three years of higher West African rainfall amounts (top diagram) in contrast to a similar period of lower rainfall amounts (bottom diagram). Note the lack of track difference along the Gulf Coast, but the quite substantial difference in the western Atlantic and along the East Coast.

July. A strong monsoon at a high-latitude position in June–July is conducive to continued abundant rainfall for the remainder of the summer. Also, the delayed influence of precipitation during the late summer and fall of the prior year through vegetation and soil-moisture processes on the amount of later available water vapor appears to also be a significant precursor influence.

TABLE 7. Annual average incidence of hurricane-related deaths in the U.S. for seasons folowing the ten wettest versus the ten driest West African early-season rainfall periods. East Coast values include the Florida peninsula

	Gulf Coast	**East Coast**	**Total U.S.**
Ten wettest years (1949–90)	10.0	47.9	57.9
Ten driest years (1949–90)	3.6	0.8	4.4
Ratio—Ten wet to ten dry years	2.8	59.9	13.1

Two forthcoming papers utilize the two predictors of tropical cyclone activity shown here. The first (Gray et al. 1992a) is concerned with seasonal forecasting by 1 December of the previous year and uses the Gulf of Guinea rainfall index in conjunction with the expected phase of the stratospheric quasi-biennial oscillation. The second (Gray et al. 1992b) deals with a 1 August seasonal forecast that incorporates both the Gulf of Guinea and the June–July west Sahel rainfall as well as other global and regional predictors.

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